National Geospatial-Intelligence Agency (NGA)

General Image Quality Equation (GIQE)

Version 5.0

16 September 2015

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000	16 Sep 2015	All – v5.0	Initial Release dtd 22 September 2015

General Image Quality Equation; GIQE version 5

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Abstract. Previous GIQEs, versions 3 and 4, were developed by NGA to predict the NIIRS (National Imagery Interpretation Rating Scale) of Electro optical (EO) and panchromatic and IR images that had been processed to film. It is reasonable to assume that such imagery had a fixed enhancement chain so these previous versions of the GIQE used image quality metrics of the enhanced image. This paper updates the GIQEs to predict the NIIRS of digital images in a softcopy display environment where image enhancements – principally sharpening and contrast adjustments - are interactive tools on the Electronic Light Table (ELT). Because the exact enhancements applied are not known in advance, this new version of the GIQE predicts NIIRS using image quality parameters (Ground Sample Distance (GSD), Relative Edge response (RER), Smear and Signal-to-Noise-Ratio (SNR)) of the un-enhanced image. In addition, the GSD has been re-defined as a compromise between the ground plane definition of GSD as used in the GIQE 4, and the normal plane GSD, as used by GIQE 3. Sensitivity analysis is presented that shows GIQE 5 predicted NIIRS as a function of sensor system design parameters including smear and Q, where Q is a key optical design quality parameter equal to λ*FN/p.

OCIS codes 110.3000, 280.4991

1. Introduction

A General Image Quality Equation (GIQE) predicts the NIIRS of an image using generic image quality metrics. NIIRS is an integer scale (presently 0 to 9) that quantifies the ability of trained imagery analysts (IAs) to perform selected visual detection and recognition tasks with imagery.

This paper is organized as follows. The next section, Section 2, provides a short history of the GIQE versions 1 through 4, and the motivation for developing a new GIQE, called GIQE 5. Section 3 describes the GIQE 5 and an overview of the three NIIRS evaluations used to estimate the equation. Section 4 presents the results of a validation study and Section 5 presents two analyses of the GIQE 5 that show its sensitivity to sensor design parameters and implications for sensor developers. The last section concludes with a summary and recommendations.

2. Background

In support of sensor developers, National Geospatial-Intelligence Agency's (NGA) predecessor organizations released two GIQEs to predict NIIRS, one in 1992 and a second in 1996. These were called GIQE 3 [1] and GIQE 4 [2]. The earlier GIQEs 1 and 2 were developed in the 1980s, and documentation no longer exists.

The GIQE 3 and 4 both assumed that image products were monochromatic film with a "standardized", processing and enhancement chain, and exploited on a light table having a zoom magnification capability. These GIQEs were estimated (by regression analysis) from Image Analysts (IA) NIIRS ratings of scenes that were well optimized with regards to image contrast via Dynamic Range Adjust (DRA) and Look Up Tables (LUTs). However the image set included well sharpened images, partially sharpened, and unsharpened images with regards to Modulation Transfer Function Correction (MTFC) using 3x3 or 5x5 sharpening filters. The case of most interest is the prediction of NIIRS of well sharpened images, although in principle, these GIQEs should also predict the NIIRS of unsharpened and partially sharpened images.

Both the GIQE 3 and 4 predict the NIIRS using Ground Sample Distance (GSD) and the image quality metrics Relative Edge Response (RER), Edge Overshoot (H), and the Signal-to-Noise Ratio (SNR) of the enhanced image after MTFC has been applied. The use of metrics that characterize the enhanced image are reasonable under the assumption that the image enhancement chain is fixed, as is the case for film products.

In the period since the release of GIQE 4, NGA and much of the remote sensing community has transitioned to a softcopy image display environment. The use of electronic light tables (ELTs) allows the image analyst (IA) to be the final arbiter as to what image enhancements are applied. In such circumstances, a GIQE that uses quality metrics of the enhanced image is difficult to implement. Experience has shown that individual IAs have their own enhancements preferences. These enhancements can change with target/background characteristics, the exploitation task, the display, and vary with the visual acuity and preferences of the IA.

In addition to the transition to softcopy, NGA has recently implemented a "Common NIIRS Policy" that requires the NIIRS for pan, IR, multispectral images to comply with a common set of design parameters:

- NIIRS will adhere to 2:1 slope relationship with GSD. Each doubling of GSD results in an integer decrement in NIIRS.
- NIIRS 5 is defined as a high quality image having a GSD of 20.8 inches from a system with

a λFN/p = 1.0 (called Q) where lambda is the average spectral band pass of the sensor (in microns), FN is the ratio of the focal length to the maximum aperture of the optics and p is the pixel pitch of sensor's detector cell (in microns).

This 'Common NIIRS Policy' motivated NGA's Image Quality and Utility (NIQU) to create a new (2008) NIIRS word criterion for each Order of Battle. These two developments have made the GIQE4 obsolete and required NIQU to develop a fifth generation GIQE that is the topic of this report.

This new GIQE differs from previous GIQEs in the following regards: use of unenhanced imagery, scope, GSD definition, RER definition, and treatment of smear. The biggest change is that the GIQE 5 uses image quality metrics of the unenhanced image to predict the NIIRS of the enhanced image. This approach assumes the NIIRS of an enhanced image is monotonic, but not necessarily linear, with the overall quality of the unenhanced image. Therefore the NIIRS of a well enhanced image can be accurately predicted from the unenhanced image quality metrics.

This new GIQE also represents a paradigm shift that actually limits the scope of the equation when compared to the previous GIQEs. It is intended to predict the NIIRS of only well enhanced images that are exploited using an ELT and displayed on a calibrated high quality liquid crystal display (LCD). The actual enhancements applied are not specified. It only assumes IAs will optimize the image to their satisfaction. These individual IA enhancement preferences will differ, but these differences are assumed to be (mostly) compensation for variations of the human visual system (see [3]) among IAs.

In addition to the use of unenhanced image quality metrics, a second objective was to expand the range of permissible target elevation angles for which the GIQE 5 equation would be applicable, where target elevation is the angle between the local ground plane and the line of sight vector from the target to the sensor. A nadir looking (90 degrees target elevation) cloud-free image is fairly uncomplicated. There is no terrain masking, no target orientation effects, and there is a commonly accepted definition of GSD. None of this is true for off-nadir images, and the problems intensify as target elevation angles decrease. Airborne imaging systems are capable of collecting images out to the horizon and are expected to provide NIIRS ratable images below 10 degrees target elevation.

To accommodate lower target elevations, the GIQE 5 re-examined the definition of GSD. The GIQE 3 defined the GSD as the pixel resolution when projected into the plane perpendicular to the line of sight. It is a function of the sensor's focal length, the size of the sensor's detectors and the line-of-sight distance. It is independent of target elevation. The GIQE 4 defined GSD as the pixel resolution when projected into the ground plane. This ground plane GSD will vary as function of target elevation, and is always greater than the normal plane GSD for non-nadir geometries.

The ground plane GSD is the default definition of GSD for most current sensor systems. But its' use is questionable for very low target elevations because it ignores the improving resolution in the vertical dimension. The GIQE 4 was estimated using images with elevation angles between 25 and 90 degrees. Expanding this range is desirable and the GIQE 5 was estimated using images with target elevations as low as 8.9 degrees. This data supports the use of a compromise GSD that is a geometric mean of the normal plane GSD and ground plane GSD.

Previous GIQEs did not directly address smear effects, although in principle, they can be included in the RER term. Analysis described in [4] and [5] show that smear is an important contributor to image quality loss and can and should not be ignored when present. Analysis presented in Section 4 shows that the GIQE 5 can accommodate smear effects through the RER term when RER is re-defined as a weighted geometric average where the along track RER is given twice the weight as the cross track RER, as defined in equation (7) provided later.

2.1 Version 3 and 4 GIQEs

The two previously published GIQEs, GIQE 3 and GIQE 4 have the same form:

$$\mathrm{NIIRS} = \mathbf{C}_0 + \mathbf{C}_1{*}\mathrm{Log}_{10}(\mathrm{GSD}) + \mathbf{C}_2{*}\mathrm{Log}_{10}(\mathrm{RER}_{GM}) + \mathbf{C}_3{*}G / \mathrm{SNR} + \mathbf{C}_4{*}H_{GM} \quad (1)$$

where:

RER_{GM} = Geometric mean Ground Sampled Relative Edge Response

GSD = Ground Sampled Distance (inches)

H_{GM} = Geometric mean Height of overshoot due to edge sharpening

G = Noise Gain due to edge sharpening, and

SNR = Signal-to-Noise Ratio.

The variables RER, H and G are calculated after MTFC enhancement. The SNR term is calculated prior to enhancement, so that SNR/G is post enhancement SNR. These terms are defined in detail in [6] and will not be repeated here. And as just discussed, the two GIQEs do use different definitions of GSD.

Table 1 below gives the values of these coefficients. A value of -3.32 for C_1 is a signature for the common

Table 1: General Image Quality Equation Coefficients

GIQE vers	C_0	C_1	C_2	C_3	C_4
3	11.81	-3.32	3.32	-1	-1.48
4 - with RER>0.9	10.25	-3.32	1.559	-0.344	-0.656
4 - with RER<0.9	10.25	-3.16	2.817	-0.344	-0.656

NIIRS policy recently implemented at NGA. It predicts a one NIIRS loss for every doubling of GSD. The GIQE 3 conforms to this policy, but the GIQE 4 does not when RER is less than 0.9. This bifurcation of the GIQE 4, depending upon the value of RER, is due in part, because NIIRS prior to 2008 did not impose a strict requirement for a 2:1 relationship with GSD.

These GIQEs appear to be a simple linear equation of Log10(GSD) term and the three quality factors, $\mathrm{Log}_{10}(\mathrm{RER})$, G/SNR and H. However there are interdependences among these terms that make it a far more complex relationship. For example, for SNRs greater than 30, optimal sharpening will typically generate RERs around 0.9 or higher. However as the SNR decreases, there is a point where RERs this large are no longer tenable because the noise would be too disruptive. So the SNR affects the predicted NIIRS directly through the G/SNR term, but also indirectly through its' relationship with RER. See [7] for additional discussion.

2.2 GIQE Version 5

GIQE 5 was developed to predict NIIRS of well-enhanced softcopy pan EO imagery using unenhanced image quality variables. It assumes an Optical Point Spread Function consistent with a conventional telescope design such as a Ritchey-Chretien or a Cassegrain, and is calibrated to predict the latest NIIRS (Post 2008, Table A1). It also assumes a Q is between 1 and 2.0 (=Nyquist sampling) where Q ($=\lambda$FN/p) is a fundamental design parameter of digital imaging systems, λ is the center wavelength of the panchromatic band, FN is the optic's f number (focal length divided by the diameter of the aperture), and p is the detector sampling pitch. See [5] for additional discussion of Q.

The GIQE 5 has a different functional form compared to the previous GIQEs because there is an interaction between un-enhanced RER and SNR that is not present when using enhanced parameters. This interaction has the effect that if the SNR is large (>50), then RER is relatively unimportant because one can apply enough sharpening to largely compensate for any loss in edge sharpness. However as the SNR decreases, the amount of sharpening that can be applied is increasingly constrained by the visibility of the noise. For very low levels of SNR (<3), the noise can be so conspicuous, it may be best to not sharpen at all. As a result, the GIQE 5 needs an interaction term that dials down the effects of RER on the predicted NIIRS as SNR increases. The GIQE 3 and GIQE 4 do not require this interaction term because the enhanced RER value already accounts for this interaction.

A major challenge for developing an IQE using unenhanced image quality parameters was the identification of the appropriate functional form for this interaction term. An IA delta-NIIRS evaluation was used to assess candidate formulations of this interaction term.

Three IA NIIRS evaluations were used in the development of GIQE 5. The first, evaluation 1, was mentioned in the previous paragraph. A second NIIRS evaluation included low and very low SNR images that helped to refine the estimates of the parameter coefficients. A third evaluation, to assess the best definition of GSD, is discussed in Section 2.3. The resulting GIQE 5 is given below. The values for the coefficients are given in Table 2.

$$\begin{aligned}\mathrm{NIIRS} = \; & \mathbf{A_0} + \mathbf{A_1}*\mathrm{Log10(GSD)} \\ & + \mathbf{A_2}*[1-\exp(\mathbf{A_3}/\mathrm{SNR})]*\mathrm{Log}_{10}(\mathrm{RER}) \\ & + \mathbf{A_4}*\mathrm{Log10(RER)}^4 + \mathbf{A_5}/\mathrm{SNR}\end{aligned} \tag{2}$$

Table 2: GIQE 5 Equation Coefficients

A_0	A_1	A_2	A_3	A_4	A_5
9.57	-3.32	3.32	-1.9	-2	-1.8

Equation (2) has no edge overshoot term, H, or gain, G, because these terms are associated with enhancement processing. In accordance with the Common NIIRS policy, the GIQE 5 NIIRS predictions follow a 2:1 relationship with GSD, and consequently, the coefficient for Log10(GSD) is -3.32. But as was discussed earlier, the definition of GSD has been altered and is neither a ground plane (GIQE 4) or a normal plane projection (GIQE 3) GSD.

The remaining terms of equation (2) above adjusts the predicted NIIRS as a function of RER and SNR. The interaction term between RER and SNR

$$3.32*[1-\exp(-1.9/\mathrm{SNR})]*\mathrm{Log}_{10}(\mathrm{RER}) \tag{3}$$

is new and has the desired property that, for large SNRs, RER has a reduced effect on the estimated NIIRS. The coefficient A_2 was set to 3.32, so that in the limit, as SNR becomes small, the resulting coefficient for $\mathrm{Log}_{10}(\mathrm{RER})$ approaches 3.32, the value used in GIQE 3.

The $\mathrm{Log}_{10}(\mathrm{RER})$ quartic term

$$-2.0*\mathrm{Log}_{10}(\mathrm{RER})^4 \tag{4}$$

is also new. It is a small adjustment for RERs > 0.3 when this term is less than 0.1 NIIRS, but is increasingly important for RER values less than 0.3. It represents a NIIRS loss, regardless of the SNR. It is associated, in part, with the deficiencies of simple 3x3 or 5x5 sharpening kernels typical of most ELTs. For more optimal edge enhancement algorithms, such as a Wiener Filter, the NIIRS loss would likely be less than predicted by (4).

The -1.8/SNR term is similar to the previous GIQEs in form and magnitude (assuming a gain G equal to 6 or so). It represents only a small adjustment to NIIRS for SNR greater than 15. But for very low SNRs, this term is an increasingly significant adjustment.

Figure 1 plots the predicted GIQE 5 NIIRS as a function of the unenhanced RER for five levels of SNR: 3, 5, 10, 20 and 50, assuming a GSD = 20.8 inches. As anticipated, this predicted NIIRS is increasingly sensitive to RER as SNR decreases.

2.3 GSD Analysis

As discussed earlier, the GIQE 4 defined GSD as the resolution of a pixel pitch when projected into the ground plane. Some image analysts believe a ground plane GSD is overly pessimistic because it ignores vertical height resolution that becomes increasingly pronounced as the target elevation decreases. This deficiency motivated Neil Gelberg [8] to propose a GSD defined as the geometric mean of the Ground Plane (GP) GSD and Normal Plane (NP) GSD, and denoted here as the weighted GSD, or GSD_W. This weighted GSD is always

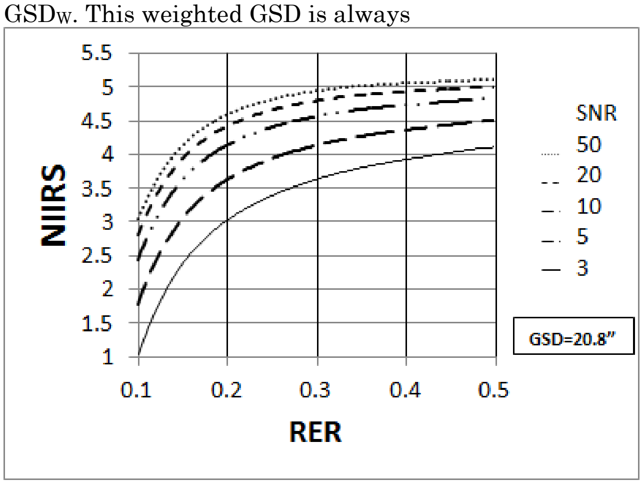

Figure 1: GIQE 5 Predicted NIIRS as a function of RER and SNR

greater than the Normal Plane GSD and less than the Ground Plane GSD for non-nadir geometries.

The relationship between NIIRS and elevation angle is even more complicated than simply the proper definition of GSD. Other factors that affect image interpretability are target attributes unique to each image: obscuration, target orientation relative to the line of sight, and target height. These factors increase the variability of the NIIRS assigned to images that are otherwise the same with regards to the GIQE 5 quality factors. To include these factors into the GIQE 5 is beyond the scope of this paper, and in fact, may be of little utility since scene content is typically not known apriori to the acquisition of the image. The increased variability of IA rated NIIRS, as the elevation angle decreases, is an unavoidable consequence of these un-modeled scene content effects.

The GSD when projected into the plane normal to the line of sight is calculated as:

$$GSD_{\perp} = \frac{\text{pixel Pitch}}{\text{focal length}} * \text{ slant range}$$

where all linear dimensions are in common units (inches, meters). It is the smallest credible value for GSD. The GSD when projected into the ground plane is calculated as

$$GSD_{GP} = GSD_{\perp} / \text{Sin(Elev Angle)}^{1/2}$$

The square root in the denominator is due to the geometric mean of the cross scan and along scan resolutions (assumed to be orthogonal). It is the largest credible value for GSD. The weighted GSD is defined to be the geometric mean of these two extremes, and is calculated as

$$GSD_W = GSD_{\perp} / \text{Sin(Elev Angle)}^{1/4} \qquad (5)$$

A third evaluation was conducted to test explicitly the suitability of each of the three definitions of GSD. Images were selected to have target elevation angles that ranged from 9.5 degrees to 89 degrees. A sub-sample of images were down sampled to a larger GSD, while maintaining the target elevation, RER and SNR. A total of 93 images were NIIRS rated. The ground plane GSD regression and the weighted GSD regression had essentially the same R^2 (=0.90), but the ground plane Log10(GSD) coefficient was equal to 2.85 ± 0.10se. (A 95% confidence interval does not include the desired 3.32 associated with a 2:1 relationship.) The weighted GSD regression was closer to the desired 2:1 relationship (3.16 ± 0.11se), and a 95% confidence interval does include 3.32. The normal GSD regression was also close to the 2:1 relationship (3.20 ± 0.16se) but had a substantially smaller R^2 (=0.80). So only the weighted GSD regression had a high R^2 and a slope that was near to the desired 2:1 relationship. These results supported the use of the weighted GSD. This conclusion is also supported in a validation study to be discussed in Section 3.

2.4 RER and Smear

The RER used in equation (2) is calculated from the system MTF that is a cascade of the optics MTF and detector MTF. Figure 2 shows the various MTF components for a Q=1 system that are modeled in this paper and also the final sensor system MTF. Equations for these MTFs can be found in [12]. Other sources of MTF loss, not modeled here, might include atmospheric turbulence and dispersion, the optics alignment and defocus, detector carrier diffusion and charge transfer, and synthetic array interpolation.

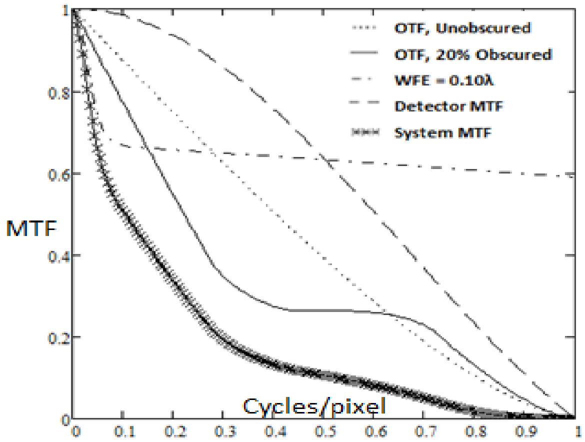

Figure 2: System Modulation Transfer Function and Component Parts

Smear is defined as the quality degradation due to relative motion between a detector and the ground over the sensor's integration time. The immediate effect of smear is a reduction in MTF in the smear direction. This in turn will reduce the RER, and through the GIQE 5, equation (2), reduce the predicted NIIRS.

In low smear cases, the RER in the x direction will be nearly equal to the RER in the y direction. But as smear increases, RER can be substantially asymmetric. In these circumstances, the GIQE 3 and GIQE 4 defined RER, without supporting evidence, as the geometric mean of the two RERs. However analysis presented here shows that if the GIQE 5 uses the geometric mean RER, it will under-estimate the actual NIIRS loss. Rather RER needs to be defined so as to give a higher weight to the lesser of the two RERs.

An important study for this analysis is Reference [4] that estimates the NIIRS loss for various amounts of smear. In this study, a linear array sensor system was modeled assuming a Time Delay and Integration (TDI) capability. S is the smear, in pixels, due to any mismatch between the scan rate and the sensor line rate, and is calculated as

$$S = N_{TDI} * \varphi * \Delta x,$$

where N_{TDI} is the number of TDI stages, φ is the number of clock cycles required to read out a TDI stage (φ =2 or 4) and Δx is the smear distance per clock cycle, in pixels, due to this mismatch. The smear, S, is in addition to a second source of smear that occurs when clocking out charge from a detector and is equal to 1/φ pixels. Figure 3 plots example Smear MTFs for S=0, 1, 2, 4 and 8 as given in [4]. When S= 0, only the clocking smear applies, and is assumed, here, to be ¼ pixel.

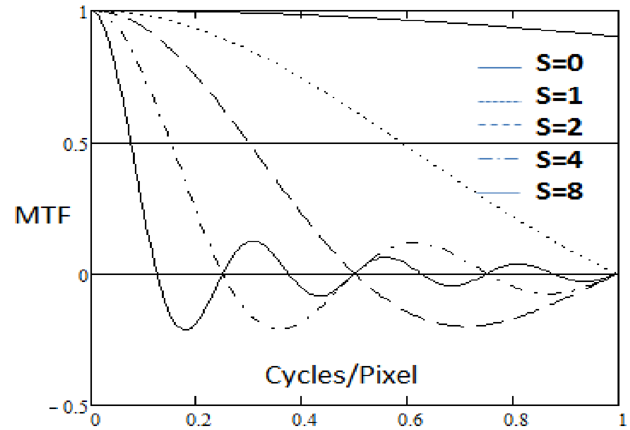

Figure 3: Smear MTFs for S= 1, 2, 4, and 8 assuming φ=4 and TDI=8

Reference [4], using SNR=50 and Q=1 images, simulated the effects of S = 0 to 8 pixels of smear using the Smear MTFs shown in Figure 3. These degraded images were then NIIRS rated by 12 expert observers, and the NIIRS loss, as a function of smear, was estimated as:

$$\text{NIIRS loss} = 0.0031 - 0.063{*}S - 0.0059{*}S^2 \qquad (6)$$

As the authors of [4] note, equation (6) is specific to the sensor system modeled, and could be expected to vary with SNR and system MTF. Even with this known limitation, it does provide a first order estimated of the magnitude of the NIIRS loss due to smear and it is in an especially convenient form when the amount of smear in an image is spatially varying, typical of scanning systems.

The data used to estimate the GIQE 5 included images with up to 4 pixels of smear. Equation (6) did accurately predict the NIIRS loss for these cases. But more broadly, it would be desirable that the GIQE 5 be internally consistent and predict the NIIRS loss calculated by (6) by simply modifying RER to include the effects of smear. The modified RER would, in this case, be calculated incorporating the smear MTF shown in Figure 6 into the system MTF, Figure 2.

To present an example case, assume Q=1, the secondary mirror obscures 20% of the primary mirror, the wave front error equals 0.1λ, and φ =4. Table 3 below shows the cross scan RER and the estimated effect of the smear on along scan RER. Also shown are the resulting geometric mean RER (RERgm) and a weighted RER (RERwt). RERwt is defined in equation (7) below.

Table 3: RER as a function of Along Scan Smear

	Along scan Smear				
	0	1	2	4	8
RER C/S	0.329	0.329	0.329	0.329	0.329
RER A/S	0.329	0.302	0.247	0.169	0.100
RER gm	0.329	0.315	0.285	0.236	0.181
RER wt	0.329	0.311	0.272	0.211	0.149

Figure 4 plots the delta NIIRS predicted by Eq. (6) and the NIIRS loss predicted GIQE 5 for three definitions of RER. All cases assume SNR = 50.

Definitions:

a) RER is defined as the geometric mean of the cross scan and along scan RERs.

b) RER is defined as the RER in the along scan direction only (worse case)

c) RER is a weighted average of RERs:

$$RERwt = (RER_{cs} * RER_{as}^2)^{1/3} \qquad (7)$$

and where RER_{cs} ($\geq RER_{as}$) is the cross scan RER and RER_{as} is the along scan RER.

Case (a) is the traditional definition of RER that is used in the GIQE 3 and GIQE 4. With it, the GIQE 5 underestimates the NIIRS loss predicted by equation (6), as shown in Figure 4. Case (b) is clearly a worse case RER, and the GIQE 5 over estimates the NIIRS loss. Case (c) uses an RER that is a 2:1 weighted geometric average of the along scan and cross scan RERs. It predicts the Eq. (6) NIIRS loss well for smears less than or equal to 8 pixels. Beyond 8 pixels of smear, there is less agreement, but the data used to estimate Eq. (6) did not include images beyond 8 pixels of smear. So the NIIRS loss has greater uncertainty for S > 8.

If the smear vector (in pixels) has both an along scan and a cross scan component, say S_{as} and S_{cs} pixels, then a simple image rotation places the smear in the along scan direction only. This rotated smear will be $S = (S_{as}^2 + S_{as}^2)^{0.5}$ pixels, and equation (7) applies and can now be used to calculate the weighted RER.

The weighted RER is always less than or equal to the geometric mean RER, and so the predicted NIIRS loss will be greater. From a sensor system designer's perspective, equation (7) implies that a loss of RER in one direction cannot be mitigated by a simple proportional increase of RER in the orthogonal direction.

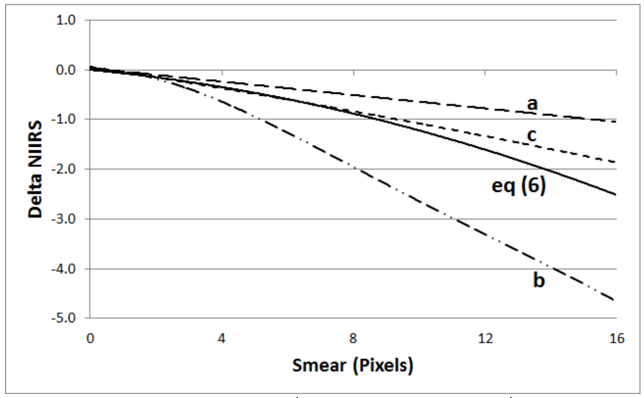

Figure 4: NIIRS loss for: a) Geometric RER, b) along scan RER, c) weighted RER, and as predicted by eq. (6)

For future reference, GIQE 5 assumes the use of this weighted RER.

3. GIQE 5 Validation Study

The GIQE 5 was developed and calibrated through a series of IA evaluations using a combination of aerial and satellite images. The results are equation (2) earlier. This equation was then tested and validated using a set of images collected by sensor systems different from those used in the initial calibration effort so as to provide a more robust validation.

3.1 Validation Experimental Design

A total of 47 **airborne** images were identified to validate the GIQE 5. The characteristics of the imagery are as below: average, (min and max).

RER:	0.41 (0.31, 0.54)
Noise std:	1.20 (1.06, 1.40)
SNR:	10.64 (4.1, 26.7)
GSD_W:	13.2 (3.3, 34.4) inches
GSD_{GP}:	18.6 (3.3, 55.3) inches
IA NIIRS:	5.9 (2.9, 7.7)
Elev Ang:	34.6° (8.9°, 87.3°)

The SNR of these images are at the lower end of the range typical of many remote sensing systems, and will exercise the RER and SNR terms of the GIQE 5 equation well. The low elevation angles cases will allow discrimination among the three definitions of GSD.

The images were chipped to targets of interest and then enhanced by experienced IAs (MTFC, TTC and DRA). Custom software was used to display the images on calibrated LCD color monitors. The noise, RER and SNRs were calculated directly from the un-enhanced images using NIQU custom software whenever engineering estimates of these variables were unavailable.

3.2 Validation Results

Figure 5 plots average IA NIIRS ratings of the 47 images against the predicted GIQE 5 NIIRS assuming the use of either the ground plane GSD, the weighted GSD, or the normal plane GSD. In each case the corner to corner diagonal dashed lines represents a 2:1 relationship between NIIRS and the designated GSD.

The Weighted GSD, case (b), has a regression slope of 1.05, very close to the desired slope of 1.0, and the 95% confidence interval easily includes 1.0 (0.964 to 1.131). This regression has an R^2 equal to 0.93 and the standard error of the estimate is 0.35 NIIRS. There is essentially no bias comparing the average NIIRS. The slopes for the other two cases, (a) and (c), are 0.88 and 1.30 respectively, and their confidence intervals do not include 1.0.

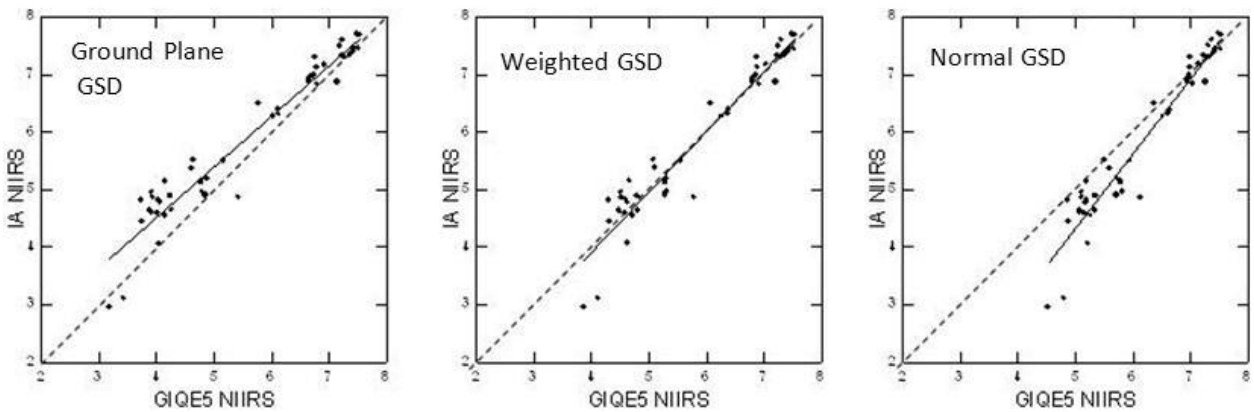

Figure 5: Validation Results, IA NIIRS plotted against GIQE 5 using three definitions of GSD

These results do validate the GIQE 5 under fairly demanding circumstances. The sample of images in this validation sample did not include extremely low SNR images (SNR < 4), so additional analysis will be presented in the next section addressing this case.

3.3 Summary Analysis Using All the Data

Figure 6 plots the average NIIRS ratings of 10-12 IAs against GIQE 5 predicted NIIRS using all the data (N=469) including the validation data set just discussed, and using the Weighted GSD. The slope is 0.973 ± 0.051se – very close to the desired value of 1.0 and the R^2 is equal to 0.90. The standard error of the regression is equal to 0.28.

The tight cluster of points between NIIRS 4 and NIIRS 5 are associated with delta NIIRS ratings used in the first evaluation, which were base-lined to a nominal NIIRS 5, and these data points clearly have significantly less residual error. If these data points are removed, (remaining sample: N = 218), the standard error increases from 0.28 to 0.40, while the other statistics, including the slope and R^2, remain almost identical. The images were binned into five SNR categories so as to have approximately the same sample size, as shown in Table 4. Figure 7 plots the standard error of the regression for each SNR bin. This analysis clearly shows the standard error increasing as the SNR decreases.

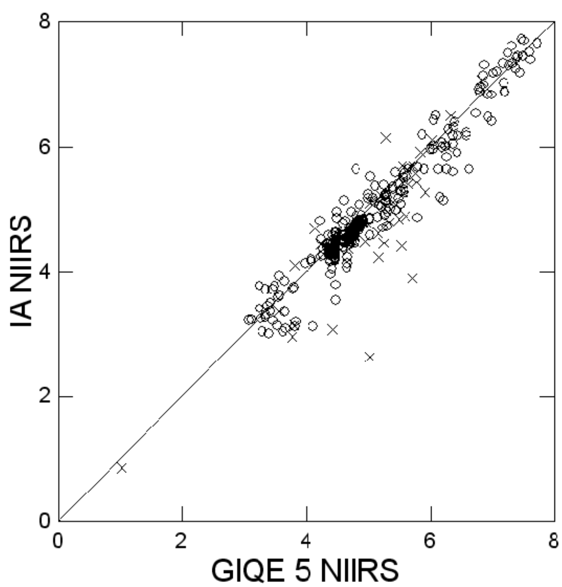

Figure 6: Average NIIRS ratings vs predicted GIQE 5 NIIRS, N= 469. Points= x are SNR <5 cases.

The large standard error for the lowest SNR bin, points designated by an 'x' in Figure 7, can be due to several factors, in addition to possible lack of fit of the GIQE 5 itself. In particular, any error in the estimated SNR, regardless of how it was obtained, will propagate to an error in the predicted NIIRS. This error becomes more exaggerated as SNR decreases due to the two reciprocal SNR terms in the GIQE 5. For example, if the SNR was estimated as 30 when its true value is 40 (a 25% error), the predicted NIIRS would have an error of 0.030 NIIRS and this is typically below the threshold of detectability. The same 25% percentage error when the true SNR is 2 (i.e.. a SNR = 1.5) results in a NIIRS error ten times larger, 0.31 NIIRS and this should be detectable.

Table 4: SNR bins and the Average Standard Errors

SNR Category	N	Standard Error
0 to 5	41	0.6
5 to 10	34	0.43
10 to 20	66	0.34
20 to 30	27	0.25
> 30	40	0.21

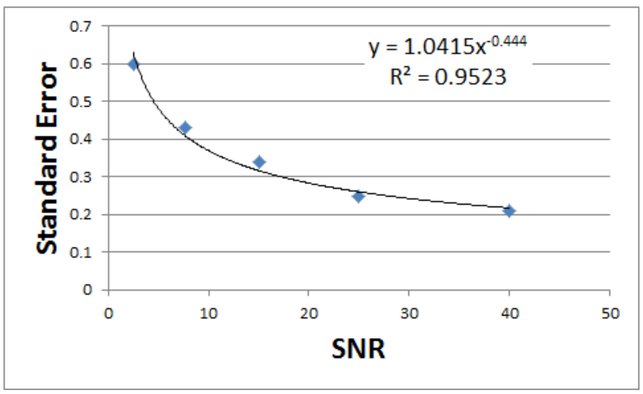

Figure 7: Standard Error of the regression as a function of SNR Bin

Another source of error in the regression is the NIIRS ratings themselves. The standard deviation of IAs rating the same panchromatic image, when obtained by comparisons to a set of NIIRS calibrated images, is typically 0.35 ± 0.1 As the SNR decreases, however, it is increasingly more difficult to rate these very low contrast but good GSDs images. This effect can be seen in Figure 8 that shows the standard deviation of NIIRS ratings from experienced IAs more than doubles as SNR decreases from 50 to 1.

The increase in error of the regression for SNRs less than 5 was noted in the GIQE 3 "User's Guide" [1], and has been noted more generally by other researchers [10] [11]. In summary, Table 4 above shows that the GIQE 5 is less precise for cases where SNR is less than 5 and should be used with caution, allowing for the increased variability of the NIIRS ratings and NIIRS predictions.

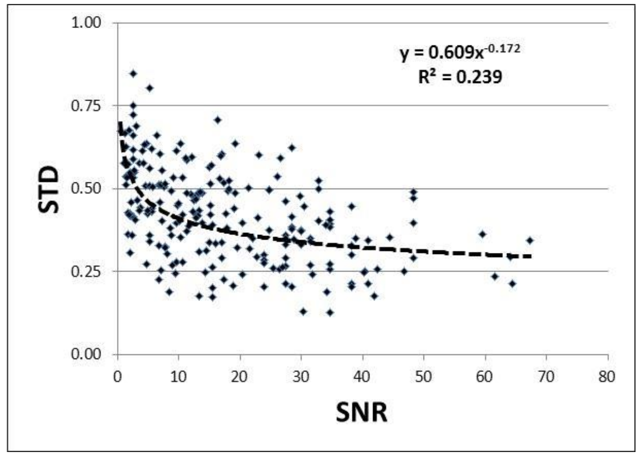

Figure 8: Standard Deviations of IA NIIRS ratings when rating the same image, N=218

4. Sensitivity Analysis

One of the intended uses of the GIQE 5 is to assess how NIIRS might behave as quality parameters are varied in ways that would model potential sensor designs. Two example analyses will be presented here. The first example extends the analysis of smear presented in Section 2.4 to include different Qs and SNRs, and to assess the robustness of predicted NIIRS loss given by equation (6). The second example estimates the NIIRS as a function of 1 < Q < 2 where Q is varied by individually changing the pixel pitch (p), the focal length (FL), or the aperture (D). The results presented here are illustrative of one aspect of the larger analysis needed to optimize a particular sensor design.

4.1 NIIRS Loss as a Function of Smear, Q and SNR

In Section 2.4, delta NIIRS was calculated as a function of smear when SNR = 50 and Q = 1. This analysis showed that when using the weighted RER, the GIQE 5's predicted NIIRS loss was essentially the same as that determined by equation (6). It would be useful to extend these results to other SNR and Q cases, and to determine the applicable of equation (6) more broadly.

Table 5 below shows the estimated along scan RER for different values of smear, and for three levels of Q=1, 1.5 and 2. The cross scan RER is given by the Smear = 0 case. These RERs are calculated assuming the same optical design as given is section 2.4

Table 5: Along scan RER as a function of Smear and Q

	Along scan RER		
Smear	Q=1	Q=1.5	Q=2
0	0.329	0.266	0.22
1	0.302	0.249	0.211
2	0.247	0.212	0.187
4	0.169	0.152	0.138
8	0.100	0.098	0.095

Table 6 shows the resulting GIQE 5 estimated NIIRS loss when SNR equals to 50 and 5. The equation (6) estimated NIIRS loss is also shown for comparison. We know from Section 2.4 that the GIQE 5 predicted NIIRS loss agrees with equation (6) when Q=1 and SNR = 50. But because the GIQE 5 predicted delta NIIRS loss depends upon the assumed sensor system parameters and SNR, there is no expectation that the GIQE 5 results should exactly agree with equation (6) for these other cases.

What Table 6 does show is that the GIQE 5 predicted NIIRS loss due to smear is not strongly related to Q for a fixed SNR. Differences are more substantial when comparing SNR = 50 to SNR =5. To be sure, the SNR needs to be below 15 (not shown here) before SNR seems to matter (i.e. a NIIRS difference greater than 0.1). Currently there are no NIIRS evaluation data that relate to these other cases, but this analysis suggests that the delta NIIRS loss due to smear is not strongly dependent on Q, or on SNR when the SNR is greater than 15. This result supports the use of equation (6) as an alternative to the more complicated approach that calculates the NIIRS loss due to smear via RER as in Table 5.

Table 6: Predicted GIQE 5 NIIRS loss as a function of Smear, Q, and SNR

	Delta NIIRS Loss				
	SNR=50		SNR=5		
Smear	Q=1	Q=2	Q=1	Q=2	Eq (6)
0	0.00	0.00	0.00	0.00	0.00
1	-0.03	-0.03	-0.05	-0.04	-0.07
2	-0.11	-0.12	-0.19	-0.17	-0.15
4	-0.33	-0.43	-0.51	-0.56	-0.35
8	-0.87	-0.97	-1.19	-1.20	-0.88

4.2 NIIRS as a Function of Q

Figure 1 earlier showed how the GIQE 5 predicted NIIRS varied as a function of RER and SNR. However, that analysis is not very realistic because RER and SNR are related when system design parameters are varied. As an example, assume the sensor design given earlier, and assume $Q = \lambda FN/p$ is varied between 1 and 2 by changing the detector pitch, p, while the remaining optical parameters are fixed. Decreasing the detector pitch will increase Q and improve the resolution, GSD, but with a concomitant reduction in image quality (RER and SNR) and an increased in the technical risk (and costs). For this analysis, it will be assumed that the sensor can be configured to provide a (nearly) constant SNR for various illumination conditions by varying the number of TDI stages and/or varying the scan rate.

Under the constant SNR assumption above, reference [6] shows that the smear component, S, defined at Q=1, increases by a factor of Q^3 as Q goes to 2. Figure 9 plots the resulting GIQE 5 predicted NIIRS as a function of Q assuming, that when Q=1, the GSD = 20.8 and the smear is one of four cases (approximated by decreasing the pixel pitch, for four levels): S = 0.0, 0.5, 0.75, or 1.0 pixels. All smear cases include a 1/4 pixel of smear due to clocking. Initially, the predicted NIIRS increase because of the better resolution (GSD). However due to the cubic relationship with Q, even a small amount of smear will eventually overcome the quality improvement due to the improved GSD.

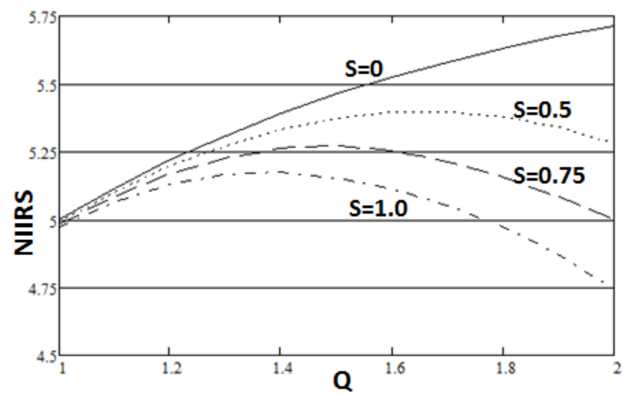

Figure 9: Predicted GIQE 5 NIIRS as Q increases from 1 to 2 for four smear levels (at Q=1), GSD=20.8 (at Q=1) and SNR = 50

Figure 9 shows the sensitivity of the predicted NIIRS to smear. For 1 pixel of smear, the predicted NIIRS at Q=2 is actually less than that predicted at Q=1. The curve with no geometric smear, S=0, in Figure 9, peaks at a value of Q = 3, and somewhat less for smaller SNRs - not shown. This may be counter intuitive since sensor systems with Q greater than 2 are diffraction limited, and no new frequencies are added for Q > 2 cases. But those frequencies below the optical cutoff will have a better system MTF because the detector MTF for these frequencies has improved. This allows for the possibility that NIIRS may continue to improve for values of Q beyond 2 when the S=0, as suggested by Figure 9. Since there were no Q > 2 cases in the GIQE 5 data set, the GIQE 5 predicted NIIRS when Q>2 is a pure extrapolation and could have large uncertainties.

Figure 9 is similar to an analysis found in reference [7] that used the GIQE 4 to predict NIIRS. This similarity shows that, while the two GIQEs are defined at different points in the image chain – pre versus post enhancements – and have different functional forms, they provide very compatible conclusions.

The relationship between NIIRS and Q, as shown in Figure 9, also applies to the case where Q is increased by increasing the focal length instead of reducing p. One difference of some importance, but unrelated to NIIRS, is the field of view is reduced by a factor of Q when the FL is increased.

The final way of increasing Q is to reduce the aperture while keeping pixel pitch and focal length the same. The GSD will now be constant and, assuming a fixed SNR, smear will increase with Q^2, not Q^3. For this case, NIIRS is monotonically decreasing with Q as shown in Figure 10.

The results given in Figures 9 and 10 are specific to line scanners having TDI capability. Sensors with 2D staring arrays will have different smear attributes than assumed here - perhaps better modeled as random jitter or a 2 dimensional random walk - and would require a different analysis.

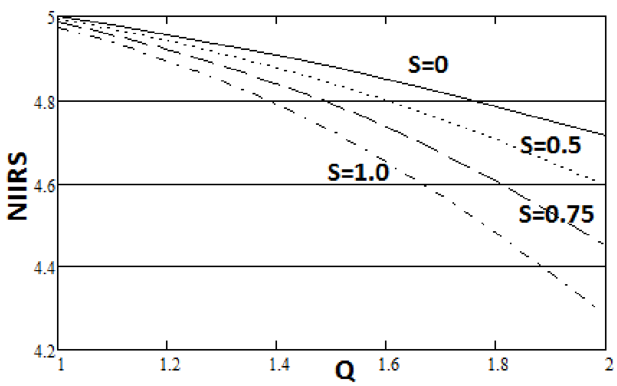

Figure 10: Predicted GIQE 5 NIIRS as Q increases from 1 to 2 by decreasing the aperture, for four levels of smear at Q=1, fixed GSD=20.8 and SNR = 50

5. Discussion and Conclusions

A revised image quality equation has been developed that uses image quality parameters of the unenhanced panchromatic EO image to predict the NIIRS of the well enhanced soft copy image. The R^2 and standard error of the regression are similar to that reported for the previous developed GIQEs. The type of imagery used in the development of the GIQE 5 is typical of many aerial and satellite remote sensing panchromatic EO sensors now in use today.

The GSD has been re-defined and is called the weighted GSD. It is the geometric mean of the ground plane GSD and the normal plane GSD. With this GSD, the GIQE 5 is consistent with NGA's Common NIIRS Policy over the large range of target elevation angles considered (8.5 to 90 degrees). Clearly there is no one best definition of GSD. Ground Plane GSD might be best for predicting the NIIRS of targets with little or no height relative to their length and width. The NIIRS of tall buildings might be best predicted using the normal plane GSD. So this weighted GSD is clearly a compromise that has been shown empirically to predict NIIRS well for images with relatively diverse scene content. One possible generalization of the weighted GSD is to allow the ¼ power exponent in equation (5) to vary between 0 and ½, depending upon scene content and the height of the targets of interest.

Many of the images with low target elevation angles would have targets obscured by neighboring targets or obscured by terrain masking effects. And all images can have obscuration due to cloud cover. It is important to note that the GIQE 5 predicts NIIRS only for the un-obscured areas of the image. Obscured targets areas would have a NIIRS of 0, but these areas are generally ignored when rating an image, unless the obscuration is particularly egregious.

Similar to the previous GIQEs, the GIQE 5 predicted NIIRS assumes images are uncompressed. For compressed imagery, a separate evaluation would be needed to characterize the NIIRS loss associated with the particular compression algorithm of interest over the intended compression rates.

The GIQE 4 was validated for IR and required only a 0.5 NIIRS adjustment to the constant term, see [13]. The GIQE 5 has not been validated for IR, but based upon the GIQE 4 results there is an expectation that the GIQE 5 can be used to predict NIIRS for IR images, unmodified due to the common NIIRS policy. This conjecture will be investigated in a follow-on report.

Removing the lowest SNR Bin, (0 to 5) in Table 4, which is view as a special case, the residual error of the regression is 0.32. This implies that any analysis to optimize a sensor system using the GIQE 5, such as that given in section 4, should be considered in this context. As a sensor system design is refined over time, it needs to be validated using real and simulated images whenever possible. This validation process would then provide the information needed to develop a more accurate IQE that would either update or replace GIQE 5. As a rule of thumb, most observers cannot distinguish two pan images that differ by a 1/10 of a NIIRS of less. So if two sensor designs provide an estimate of NIIRS that differ less than this, other sensor characteristics should dominate the analysis such as cost, technical risk, schedule, etc.

Sensor system procurements often include a NIIRS specification that requires the sensor system to achieve a specific NIIRS level at some predetermined distance and configuration. Such specifications are very understandable from the user's perspective, but from the developer perspective, introduces risks that are difficult to quantify. It puts a very high accuracy burden on analytic tools such as the GIQE 5.

Because of the uncertainty of the GIQE 5's NIIRS prediction, a prudent and recommended approach would be to select a sensor design that over achieves a NIIRS specification by 0.1 to 0.2 NIIRS, maybe more. This cushion will provide some level of insurance that the sensor system will actually deliver the required NIIRS. The actual size of this cushion should balance the costs of over achieving NIIRS performance with the cost of not meeting the NIIRS requirement.

Sensor developers need to also consider how the NIIRS performance of the sensor is to be tested. In practice, the only way to perform this test is to conduct a NIIRS evaluation using a large sample of images and observers. This is a very specialized often expensive activity, and the resulting NIIRS ratings have their own uncertainties that can complicate the interpretation of the evaluation. The sensor provider and the sensor procurer may come to different conclusions, given the uncertainties to these NIIRS ratings, should the test evaluation indicate the sensor is close but does not quite meet the NIIRS specification. In statistical terms, this is a matter as to whether the null hypothesis puts the burden of proof on the developer or the procurer. Conflicts can be avoided if a detailed NIIRS testing protocol, including sample sizes, is included in the procurement document.

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